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Study of cluster structures in ^{10}Be and ^{16}C neutron-rich nuclei via break-up reactions

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Abstract

Projectile break-up reactions induced on polyethylene (CH_2) target are used in order to study the spectroscopy of ^{10}Be and ^{16}C nuclei. For the present experiment we used ^{10}Be and ^{16}C beams delivered by the FRIBs facility at INFN-LNS, and the CHIMERA 4π multi-detector. ^{10}Be and ^{16}C structures are studied via a relative energy analysis of break-up fragments. The ^{4}He+^{6}He break-up channel allowed us to study the spectroscopy of ^{10}Be; in particular we find evidence of a new state in ^{10}Be at 13.5 MeV excitation energy. The ^{16}C nucleus is studied via ^{6}He-^{10}Be correlation; we find the fingerprint of a possible state at about 20.6 MeV.

1 Introduction

The investigation of cluster structures in neutron-rich nuclei is an important tool to explore the behaviour of nuclear forces in few body interacting systems [1]. In presence of extra neutrons clustering effects could assume very different features from the α clustering in self-conjugated nuclei. These neutrons can assume the role of covalent particles acting as a glue-like between the α cluster centers and leading to the so called nuclear molecules [1].

In this complex scenario, beryllium and carbon neutron-rich isotopes assume a very important role thanks to their possible, respectively, dymeric and trimeric molecular structures [1].

An interesting neutron-rich beryllium isotope is the ^{10}Be, for which the spectroscopy is still not fully understood. This nucleus is characterized by a deformed ground state [2] on which a positive parity rotational band is built. While the 2^+ member of the $0^+_{g.s.}$ band is known, the subsequent members assignment is still missing. For example, the 4^+ member, predicted at about 11–12 MeV, was initially claimed by Bohlen et al. [3] and after contradicted by Suzuki et al. in a very recent paper [4]. A negative parity rotational band with a 1^- state at 5.96 MeV as band-head is also reported in [1]. A molecular band is also built on the 0^+ state at 6.18 MeV, strongly characterized by a $\alpha : 2n : \alpha$ configuration [2]. For this band, the 2^+ state has been found at 7.54 MeV and the subsequent 4^+ member was assigned in Ref. [5] and in recent ^{6}He+^{4}He inverse kinematic resonant elastic scattering experiments [4].

The carbon isotopic chain has recently been object of several studies [6–10]. Three centers molecular structures could be present in ^{16}C, as predicted in a very recent theoretical calculations [11], where some linear chains, also with parity-asymmetric nature (i.e. ^{10}Be+α+2n like configurations), and

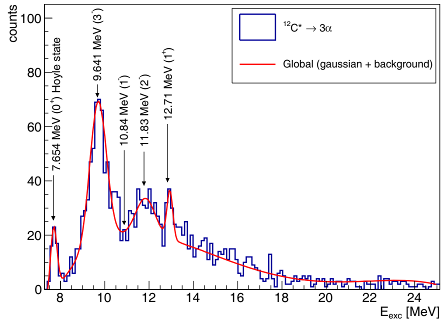

Figure 1: (color online) 3α relative energy spectrum (blue line). The red line is the result of a multiple parameters fit of the data. The fit is obtained by considering the states indicated by arrows.

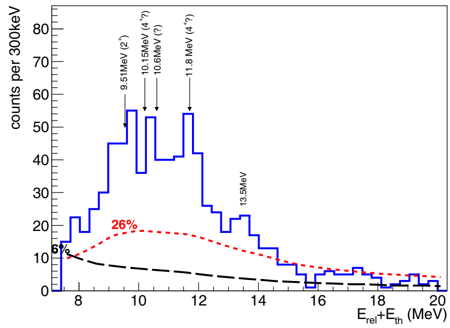

Figure 2: (color online) ^{10}Be relative energy spectrum for the ^{4}He+^{6}He break-up channel. The red and the black dashed lines represent, respectively, the simulated detection efficiency for inelastic scattering on proton and carbon

triangular configurations are pointed out above the helium disintegration threshold. However, the spectroscopy of ^{16}C is extremely poorly known and an experimental evidence of these states is still missing. For this reason, ^{16}C has recently attracted a large interest [9, 10], but very few data have been reported and no definitive conclusions can be drawn.

In the present paper we report new results on the spectroscopy of ^{10}Be and ^{16}C excited states above the cluster emission thresholds, investigated via sequential projectile break-up reactions. Reaction products have been detected by using the Chimera array. From a relative energy analysis of break-up fragments we found indications of a possible state at about 13.5 MeV in ^{10}Be. For the ^{16}C nucleus, the ^{6}He+^{10}Be correlations suggest the presence of a new state at about 20.6 MeV.

2 Experimental details

The experiment was performed at the FRIBs facility of the INFN-Laboratori Nazionali del Sud (LNS). A fragmentation beam, mainly constituted by ^{16}C, ^{13}B and ^{10}Be at 56 MeV/u, was produced starting from a 55 MeV/u ^{18}O primary beam impinging on a ^{9}Be production target. A tagging system [12], made by a Micro Channel Plate (MCP) ad a Double Side Silicon Strip Detector (DSSSD) was used in order to provide a particle by particle identification of the fragmentation cocktail.

Break-up reactions have been induced on a polyethylene CH_2 target. For the present experiment we have selected reaction products from the ^{1}H,^{2}H,^{12}C(^{10}Be,^{4}He^{6}He) and ^{1}H,^{2}H,^{12}C(^{16}C,^{6}He^{10}Be) reactions. To obtain spectroscopic information on ^{10}Be and ^{16}C nuclei we have measured masses, energies and flight directions of the corresponding break-up fragments with the CHIMERA 4π multi-detector [13]. Particle identification was carried out via the ΔE-E identification technique, by using the energy loss of the particle inside the first detection stage of the Chimera device (Si, 300μm) and the energy residual in the last stage (CsI(Tl) scintillator, $\approx$ 12 cm).

3 Data analysis

The ^{10}Be and ^{16}C structure has been studied via a relative energy analysis of break-up fragments. The excitation energy of the projectile nucleus before decaying has been reconstructed thanks to the relation $E_x = E_{rel} + E_{thr}$, where E_{rel} is the relative energy of the break-up fragments, obtained from the experimental data, and E_{thr} is the energy decay threshold of the selected break-up channel.

In order to check our experimental technique, we have studied 2α and 3α kinematical correlations. In the first case we have found evidence of a prominent peak corresponding to a relative energy of about 91 keV, compatible with the emission of α particles from the decay of ^{8}Be ground state, and a large bump at about 3 MeV relative energy, produced by the first excited state of ^{8}Be. In Fig. 1, is reported the 3α relative energy spectrum obtained by including the data from all the available beams. In this case we have found evidence of the population of Hoyle state (7.654 MeV) and also some other excited states in ^{12}C, indicated by the arrows. The red line is the result of a global fit, obtained by including the populated excited states and a polynomial smooth background. As clearly visible from Fig. 1 the fit well reproduces the behaviour of experimental data, providing a further confirmation of the validity of the present analysis.

3.1 ^{4}He-^{6}He correlations: the structure of ^{10}Be

The ^{4}He-^{6}He correlations have been used to study the spectroscopy of ^{10}Be. In this case we found the relative energy ($E_{rel} + E_{thr}$) spectrum reported in Fig. 2. Despite the limited resolution and statistics, the spectrum exhibits peaks corresponding to excited states known in literature and indicated by

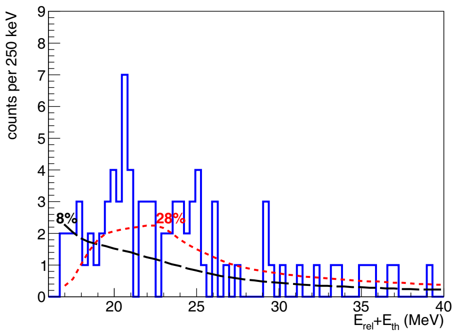

Figure 3: (color online) ^{16}C E_{rel} spectrum for the ^{10}Be+^{6}He break-up channel. The red and the black dashed lines represent, respectively, the simulated detection efficiency for inelastic scattering on proton and carbon

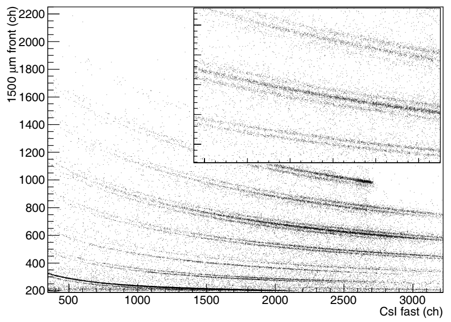

Figure 4: (color online) ΔE-E identification matrix obtained from a calibration run ^{16}O+CH_2 of the CLIR experiment. The insert shows a zoom of the boron, carbon and oxygen line.

arrows. It is noticeable the presence of a bump corresponding to an excitation energy of about 13.5 MeV, not previously observed in ^{10}Be, being the possible evidence of a new state. To check if the observed peak can be really ascribed to an excited state in ^{10}Be we evaluated the detection efficiency. This contribution was calculated via a MonteCarlo simulation. We performed two different simulation taking into account the different possible target nuclei. The obtained efficiency curves are represented by the dashed lines in Fig. 2 for the excitation on hydrogen (red line peaking at 26%) and carbon (black line peaking at 6%). In both cases the contribution is smooth, confirming the possibility to attribute the 13.5 MeV peak to the possible existence of a new state in ^{10}Be.

3.2 ^{10}Be-^{6}He correlations: the structure of ^{16}C

The ^{16}C nucleus has been investigated via the ^{6}He-^{10}Be correlations. The corresponding relative energy spectrum is shown in Fig. 3. The spectrum, with a very low statistics, shows the appearance of an yield enhancement at about 20.6 MeV excitation energy. Also in this case the simulated efficiency doesn't show any sharp peak, ant therefore it could be the evidence of a new state in ^{16}C, energetically compatible with a liner state predicted in [11]. Interestingly, a similar yield enhancement, but with lower statistics, has also been reported in both the previous works [9, 10].

4 Conclusions and future perspectives: the CLIR experiment

In conclusion, the structure of ^{10}Be and ^{16}C is investigated via break-up reactions induced by radioactive beams produced at the FRIBs facility (LNS).

We find the possible evidence of a new state in ^{10}Be at about 13.5 MeV in the ^{4}He+^{6}He disintegration channel. The ^{16}C is studied via the ^{6}He-^{10}Be correlations finding also evidence of a possible new state at about 20.6 MeV, even with an extremely low statistics.

Very recently, we have performed a new experiment (CLIR at LNS) with the aim to obtain more information on ^{16}C structure following the suggestions of the present work. The new experiment was carried out by coupling the CHIMERA device to the FARCOS array, covering the most forward directions. As an example of the capabilities of this new device, we report, in Fig. 4, a typical ΔE-E plot obtained from the CLIR data. As clearly visible, the identification is present in the whole Z domain, confirming the possibility to improve the present results.

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